

Compensation of eddy-current-induced magnetic field transients in a MOT

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The design and implementation of a current driver for the quadrupole coil of a magneto-optical trap are presented. The control and the power stages of the driver, both based on a push-pull configuration with high-speed transistors, are separated, allowing for a protection of the control electronics. Moreover, the coil current can be set by an analog voltage, a feature that makes possible both fast and adiabatic switching of the quadrupole magnetic field. In order to compensate magnetic field transients induced by eddy currents, the driver allows a quick reversal of the quadrupole coil current providing in such a way the required magnetic flux compensation. From a fit to the measured magnetic field transients, we have extracted the decay constants which confirm the efficiency of the compensation. Furthermore, we measured the influence of eddy currents on a sample of cold caesium atoms, testing at the same time the ultimate performance of the driver for our applications. The results show that the implemented electronic circuit is able to reduce substantially the transient effects with switching times of the magnetic field below 100 μ s.

I. INTRODUCTION

Magnetic field gradients play a central role in the preparation of cold atomic samples in magneto-optical traps (MOT). However, for many experiments involving cold atoms the presence of magnetic field gradients is unwanted. This means that, following the preparation of a cold atomic sample in a MOT, the time interval that we have at our disposal to perform an experiment is, to some extent, determined by the time required to turn off completely the current flowing through the coils that produce the quadrupole magnetic field of the MOT. More precisely, is the time needed to bring the magnetic field gradient to zero that sets the ultimate limit.

The current flowing in the coils can be brought to zero in several microseconds using the common technique that employs a suppression diode for switching inductive loads [1]. To bring the magnetic field to zero is more difficult since the fast change of the magnetic flux, produced by the coil current, induces eddy currents in the metallic parts adjacent to the coils. These currents will produce a

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time and spatially varying magnetic field that dies out typically in several milliseconds, depending on the experimental setup.

For a MOT, the negative effects due to magnetic field transients (and their associated gradients) generated by eddy currents are seen immediately. This parasitic transient washes out the sample of cold atoms disturbing, for instance, experiments like loading of optical dipole traps. In particular, in our experimental setup the metallic environment around the coils producing the magnetic quadrupole field is different or asymmetric for the two coils and consequently, the trap center moves during the switching transient accelerating the atoms, an effect which is deleterious for transferring the atoms into the optical trap. Yet in another field of research as magnetic resonance imaging (MRI) [2], the eddy-current-induced gradients reduce the signal to noise ratio degrading the quality of the obtained images.

It is possible to find different proposals for the compensation of eddy currents. A method based on gradient with pre-emphasis correction [3] is employed in, for example, MRI [4] and particle storage rings [5], but it requires the monitoring of the magnetic field in order to implement a closed-loop compensation. Also for MRI and nuclear magnetic resonance (NMR), radiofrequency shielding of the gradient coils has been developed [6]. Another more interesting, for our purposes, compensation scheme has been recently implemented by Dedman *et al.* for fast switching of magnetic fields in a MOT [7]. In their proposal two power MOSFET are used to switch off or reverse the polarity of the current flowing through the coils, which allows switching times for the magnetic field of around $350\ \mu\text{s}$. However, it is our belief that the performance of the circuit can be improved in two main directions. In terms of protection, it is important to avoid the use of high voltage power supplies that can seriously damage the control voltage source (a PC card, for example) in case of failure of the transistors. And, on the other hand, to allow an analog control of the amount of current fed to the coils, a relevant feature for applications like for example the preparation of cold samples in the Cs atomic fountain clock [8], where it is necessary to combine fast as well as adiabatic switching of the quadrupole magnetic field.

Here we propose a current driver that combines high-speed switching transistors on the control stage of the circuit and power switching bipolar transistors to handle the coils' current. Such a design allows the use of stable low voltage (max. 10 Volts) low current (max. 10 Amps) standard laboratory power supplies, fast and adiabatic switching of magnetic fields, and is as practical to implement as the MOSFET solution. We also provide the design considerations to help the interested reader in choosing the proper component specifications for her/his particular application.

II. FAST SWITCHING CURRENT DRIVER DESIGN

Usually, the magnetic field $\vec{B}(t)$ transient properties are measured with a pick-up coil which generates a voltage

$$V_p(t) = -N \frac{d\Phi(t)}{dt}, \quad (1)$$

being N and $\Phi(t) = \int \vec{B}(t) d\vec{S}$ the number of turns of the coil and the magnetic flux sensed by it, respectively. Therefore, choosing the coil area S_c such that the field across it is homogeneous, $V_p(t)$ will provide a direct measurement of $\frac{dB(t)}{dt}$. Qualitatively, the ideal (desired) magnetic field switching waveform can be represented by a square pulse and, in this case, the voltage measured by the pick-up coil can be mathematically described by the expression $V_p(t) = -NS_c B_{eff}(\delta(t_1) - \delta(t_2))$, where B_{eff} , $\delta(t)$, t_1 , and t_2 are the effective magnetic field amplitude, the Dirac delta function and the time instants at which the transitions take place, respectively. Nevertheless, the actual magnetic field transient waveform shows exponential transitions characterized by a time constant determined mainly by two effects: the Lenz effect and the existence of eddy currents induced in the metallic structures close to the coils producing the quadrupole magnetic field.

Just as a reminder, the influence of eddy currents can be studied with the simple electric circuit model presented in Fig. 1. The elements L and r represent the inductance and the wire resistance of the MOT coils, respectively. The metallic environment of the coils can be described by the inductance L_m and the resistance R_m .

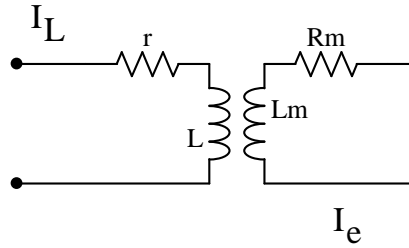


FIG. 1: Modelling of induced eddy currents.

From the equations of the time evolution of the coil I_L and induced eddy I_e currents, it is not difficult to notice that the transient behaviour of those currents is characterized by the decay constants

$$\frac{1}{\tau_{\pm}} = -\frac{1}{2(1-k^2)}\left(\frac{1}{\tau} + \frac{1}{\tau_m}\right) \pm \frac{1}{2(1-k^2)}\sqrt{\left(\frac{1}{\tau} + \frac{1}{\tau_m}\right)^2 - 4(1-k^2)\frac{1}{\tau\tau_m}}, \quad (2)$$

where $\tau = L/r$ is the Lenz effect time constant, $\tau_m = L_m/R_m$ is the decay constant associated to the metallic surrounding, and k is a coupling parameter defined by the mutual inductance $M^2 = k^2 L L_m$. Consequently, any measured magnetic field transient can be mathematically described by a superposition of two exponential terms with time constants defined by the quadrupole coil parameters and the properties of the surrounding metallic environment. This means that one way for checking the compensation of eddy-current-induced magnetic field transients will be to reduce the double exponential behaviour of the measured transient to a single one. As we will see later, the designed driver can compensate not only the effect of eddy currents but also speed-up magnetic field transients.

In terms of safety, there are two relevant factors to be considered in order to design a current driver for switching the MOT coils. One is the back induced *emf* when the current is switched off, and the other is the maximum stored magnetic energy. In our case, for a resulting inductance L of the coils of $393 \mu\text{H}$ (wire resistance $r = 0.7 \Omega$) the induced *emf* is

$$emf = -L \frac{dI_L}{dt} \approx -60 \text{ V} , \quad (3)$$

for 15 A current change in about $100 \mu\text{s}$. Concerning the stored magnetic energy E , for 15 A of current we get

$$E = \frac{1}{2} L I_L^2 \approx 44.2 \text{ mJ} . \quad (4)$$

In the Fig. 2 the current driver designed to switch the MOT coils is presented. The current supply for the coil is implemented using the power bipolar transistors 2N2955 and 2N3055, intended for power switching circuits. The operation of the power transistors is controlled by the control pulse V_{IN} and the push-pull emitter follower stage realized by the high-speed switching transistors 2N2219 and 2N2905. These transistors, together with the operational amplifier, provide the necessary isolation of the control pulse source from the high power stage of the circuit.

During the transitions, the power transistors must be able to handle the developed *emf* and therefore, we need to choose them with an emitter-collector breakdown voltage of at least the back induced voltage. In case of failure of the power transistors, usually the collector is short to the base and, in that situation, it is up to the switching transistors to handle the back induced *emf*. For this reason, we need to choose switching transistors with a collector-base breakdown voltage, again, of at least *emf* to protect the control electronics. Apart from these considerations, the diodes $D1$ and $D2$ provide a decaying path for the energy accumulated in the coils and another piece of protection for the low voltage electronics [11].

When the current through the coils is switched from some value to zero, the coils alone induce a transient with a decay constant $\tau = L/r$ of around 0.6 ms (Lenz effect). This time constant can

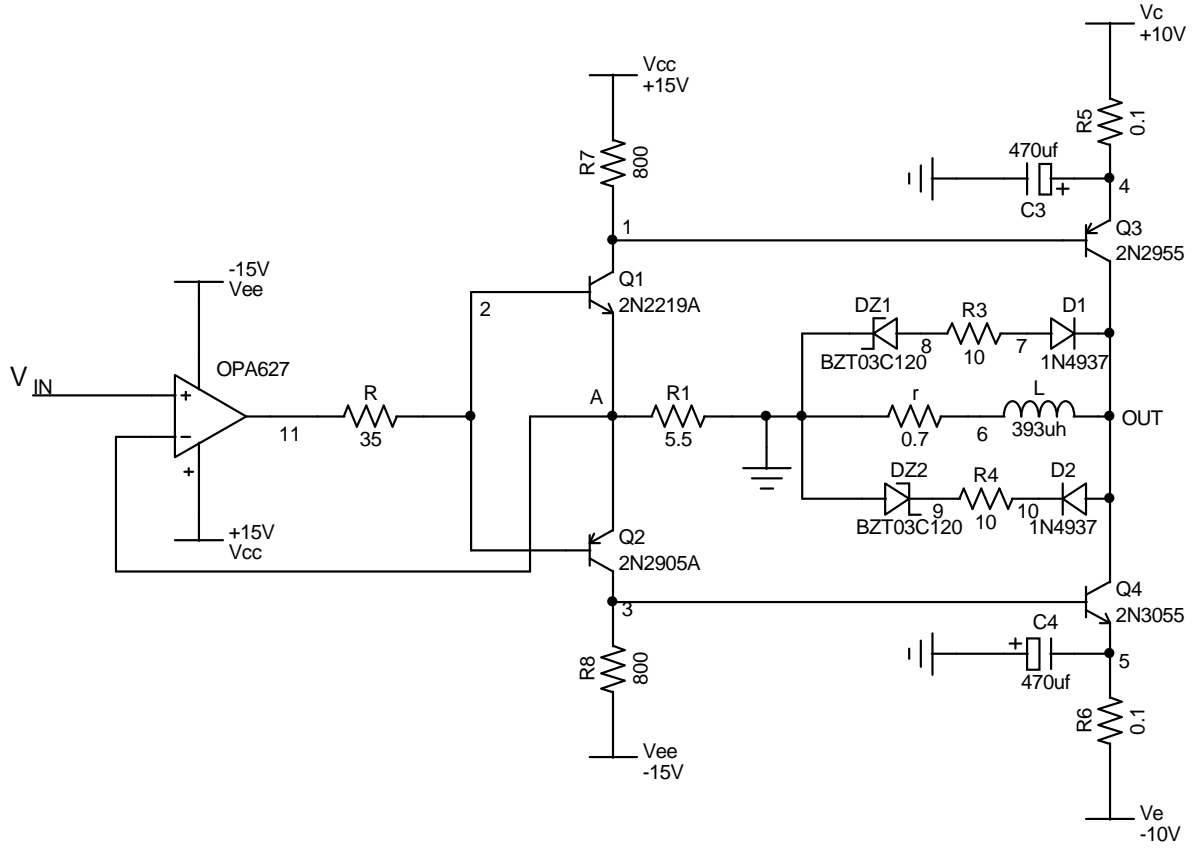


FIG. 2: Bipolar current supply for fast switching of the magnetic field.

be reduced by adding a resistor in the decaying path of the current. In the present circuit, we have added a 10Ω resistor, reducing the decay constant in that way to $36.7 \mu\text{s}$. On the other hand, the use of the Zener diodes $DZ1$ and $DZ2$ increases the protection of the circuit. They limit the voltage across the coils during the transitions and transform the long exponential decay due to $D1$ and $D2$ into a linear decay. Now, let's have a closer look into the functioning of this circuit.

Positive polarity of the control voltage

When the control input voltage V_{IN} is positive, $Q1$ is forward biased while $Q2$ is cut off. In this situation, the current through $R1$ is equal to the emitter current of $Q1$

$$i_{E1} = -\frac{V_{IN}}{R1} , \quad (5)$$

and therefore, the current flowing into the base of $Q1$, with a dc current gain β_1 , is

$$i_{B1} = \frac{V_{IN}}{R1(1 + \beta_1)} . \quad (6)$$

Since the base current necessary to put the power transistor $Q3$ into conduction equals the collector current of $Q1$ then, the current that flows through the collector of $Q3$, with a dc current gain β_3 , is

$$i_{C3} = -\frac{\beta_1\beta_3}{R1(1+\beta_1)}V_{IN} . \quad (7)$$

At this point, we know that $Q3$ is conducting. So, the diodes $D1$ and $D2$ are reverse and forward biased, respectively. Nevertheless, the voltage at the node OUT is inferior to the Zener voltage of $DZ2$ and consequently, very little current flows through $R4$. This means that the current in the coils I_L is the same as the current in the collector of $Q3$, namely

$$I_L = -\frac{\beta_1\beta_3}{R1(1+\beta_1)}V_{IN} . \quad (8)$$

Negative polarity of the control voltage

In case of negative control voltage, the analysis proceeds as above with the appropriate dc current gains of the transistors in the final expression of the coils' currents.

Zero control voltage

Let's suppose now that the voltage at the input node IN is zero. In this situation the current through $R1$ is zero since its terminals are at the same voltage level. Therefore, no current flows in the $Q1$ and $Q2$ collectors and consequently, the collector currents of $Q3$ and $Q4$ are also zero and so, no current flows into the coils.

Finally, from the expression of the coils' current, Eq.(8), it can be seen that the level of this current can be adjusted, or controlled, by the applied voltage V_{IN} at the input node of the circuit, an important feature for applications where adiabatic switching of the magnetic field gradient is required. Moreover, having fixed the resistor $R1$ and the dc current gains of the switching transistors, it is possible to increase the current limit by choosing power transistors with different β_3 (β_4).

From the preceeding analysis it is clear that the other sensitive elements of this circuit are the resistors R and $R1$, chosen as follows. Assuming a reduction of β_3 (β_4) from 20 to 5 for a peak coils' current of 10 A, we will need at the base of $Q3$ a current of 2 A to maintain it into conduction. Therefore, for a maximum input control voltage of 10 V the resistor $R1$ is 5 Ω . On the other hand, to find the specification of the base resistor R , we demand the output voltage of the operational

amplifier to be 2 or 3 % below its supply voltage, ± 15 V in our case. This yields the following criterion for R

$$R \leq \frac{12 - V_{IN} - V_{BE1}}{I_{B1}}. \quad (9)$$

If we take the dc current gain β_1 of the switching transistor $Q1$ to be 70, we obtain a peak base current I_{B1} of 28.6 mA and, for 10 V of control voltage, $V_{BE1} = 1$ V, we get for our designed circuit that $R \leq 35 \Omega$.

III. SIMULATIONS AND EXPERIMENTAL RESULTS

The behaviour of the current driver circuit in Fig. 2 has been simulated using TopSPICE 6.97 [9] and the results of those simulations are presented in Fig. 3. In this figure we show the coils' current and back induced *emf* transient responses of the circuit to a control voltage pulse of 1 ms duration. The input voltage level was changed by 10 V (from -5 V to +5 V).

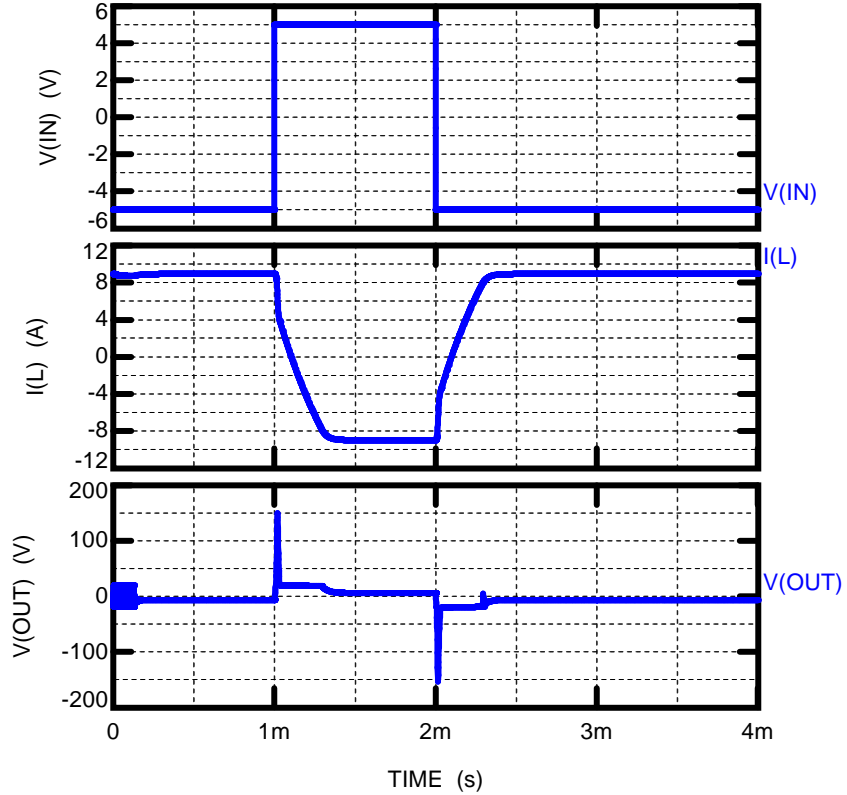


FIG. 3: Current and back emf responses of the current driver.

As we can see in Fig. 3, the current flowing through the coils, at the beginning ~ 9 A, decays to zero very fast (in around $100 \mu\text{s}$). The initial fast almost linear decay is dominated by the effect of

the resistor $R4$. Then, the current decay is controlled by the action of the Zener diode $DZ2$. The total transition time for reversing the current polarity from +9 A to -9 A is thus around 340 μs . For these control voltage and current settings, the back induced voltage during the transitions is close to 150 V.

Since the switching time of the magnetic field depends on how much current was flowing in the coils before the transition started, we also performed simulations for lower input control voltages. When the input voltage was changed from -0.5 V to +0.5 V, total switching times of the order of 100 μs are obtained, with the corresponding reduction in the back induced *emf*.

So far the analyzed results concerned the behaviour of the current flowing in the coils. However, the switching characteristics of the magnetic field itself are different because of the effect of eddy currents. For that reason, our next step was the study of magnetic field transients when the coils are driven by the circuit designed in the last section. We measured the magnetic flux transient using a small (compared to the MOT coils) critically damped pick-up coil ($L_p = 7 \mu\text{H}$ inductance and 0.1Ω wire resistance) connected in parallel with a capacitor ($C = 2.2 \mu\text{F}$) and in series with a 3.3Ω resistor. The capacitor limits the frequency bandwidth of the sensing circuit making the measured magnetic flux rate less susceptible to high frequency magnetic field noise generated by, e.g., radio stations, and the resistor value is chosen in order to obtain critically damped oscillations when the pick-up coil is kicked by a fast magnetic flux change. We placed the pick-up coil midway between the MOT gradient coils where the atomic cloud is normally formed, that is to say in the position occupied by the quartz cell (qc) in the Fig. 4. This location was chosen because it is at this point that the magnetic field produced by the MOT coils is zero and consequently, by symmetry considerations, any detectable variation of the magnetic field there is directly related to eddy currents. It can be clearly seen from the picture that the two gradient coils (tc and bc) are surrounded by different metallic components, being the bottom coil on an aluminium plate. When the magnetic field produced by these coils is switched off, it will create eddy currents with a spatial distribution, generating an unwanted magnetic field gradient.

As a reference measurement, we used a commercial current supply with switching times on the order of hundreds of microseconds to drive the current I_L in the quadrupole coil. The transient response when the current was switched off from an initial value of 3.1 A is shown in Fig. 5. As it can be seen in that figure, the duration of the measured settling time was around 10 ms, much larger than the power supply switching time and therefore, attributed to the influence of magnetic field transients due to eddy currents. Together with the experimental points, is also shown in Fig. 5 the best theoretical fit (solid line), given by a superposition of two exponentials with time

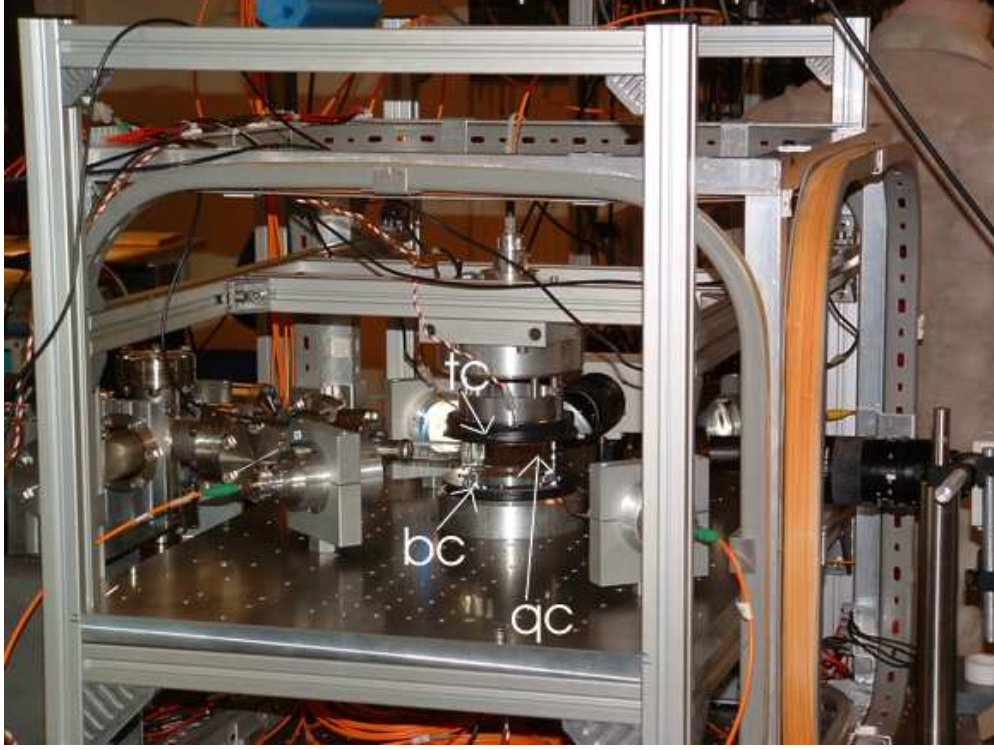


FIG. 4: Experimental setup. When measuring the magnetic flux transients associated with eddy currents, the pick-up coil is placed in the position occupied by the quartz cell (qc), between the top (tc) and bottom (bc) gradient coils (black rings). At this point the magnetic fields produced by the tc and bc coils cancel and we are more sensitive to any magnetic flux generated by eddy currents.

constants of $1.97(17)$ ms and $0.80(18)$ ms, respectively. Since these characteristic times are greater than the expected value corresponding to the Lenz effect alone ($36.7 \mu\text{s}$), we conclude that we have an important influence of eddy currents in the measured magnetic field transient.

The first test of the designed circuit (Fig. 6) was the measurement of the switching waveform corresponding to the voltage across the MOT coils, a quantity equivalent to the simulated $V(OUT)$ in Fig. 3. The first voltage spike in this trace was obtained when the coil current was switched on, to 6.6 A. For the second one, the current was reversed from 6.6 A to -3.7 A, before setting it to 0.

As expected, the duration of the transients were on the microsecond time scale. However, in order to draw any conclusion about the compensation of the effects due to eddy currents, a detailed look at the magnetic flux transient is required. This is done in Fig. 7(a) and (b). These measurement were taken when the current in the MOT coil, initially 6.6 A, was briefly reversed to -3.7 A before setting it to zero (as in the middle voltage spike in Fig. 6).

Initially, we tested the compensation of the magnetic flux induced by eddy currents. The result of this measurement is presented in Fig. 7(a), obtained when the Zener diodes $DZ1$ and $DZ2$ are

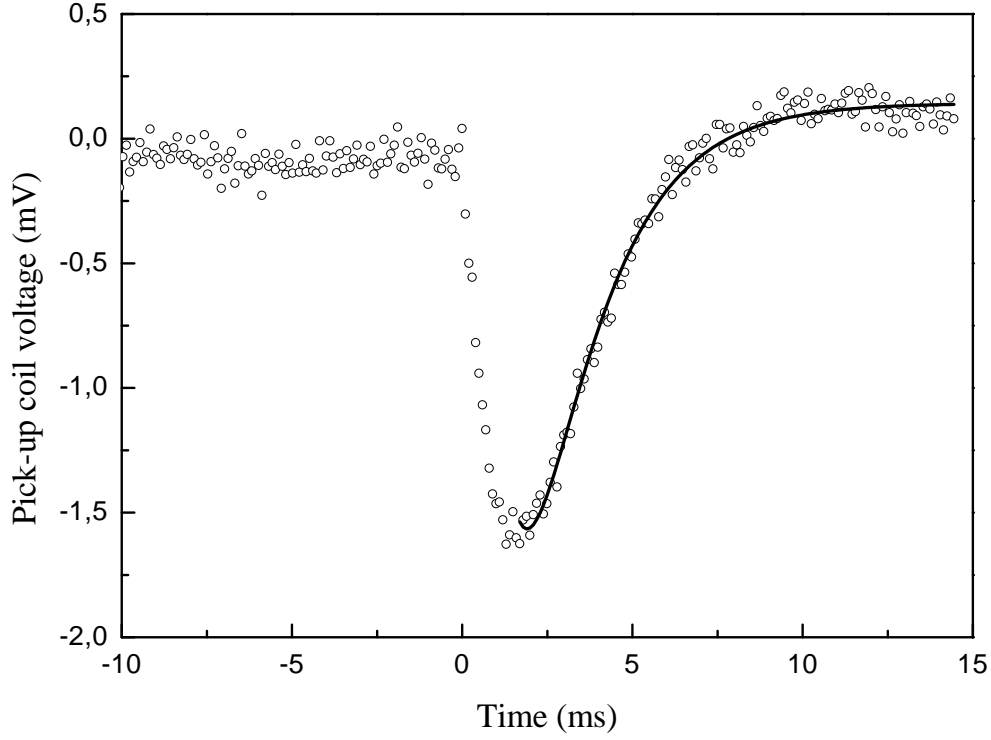


FIG. 5: Pick-up coil voltage for an initial nominal current in the coils $I_L = 3.1$ A. The two exponential fit (solid line) gives decay constants equal to 1.97(17) ms and 0.80(18) ms.

each replaced by a short and therefore, we allow more current to flow through the protection diodes $D1$ and $D2$ when the back induced *emf* appears. In this figure, we attribute the initial exponential decay (dashed line) with a time constant of $150\ \mu\text{s}$ to eddy currents. This decay is shortened down to around $40\ \mu\text{s}$ when the current is reversed, leaving the single exponential behaviour (solid line) characterized by a time constant of $32.57(2)\ \mu\text{s}$, in good agreement with the modified time constant of the Lenz effect. The overall settling time of the transient is about $190\ \mu\text{s}$.

Since with the designed driver we are able to provide a larger dI_L/dt compared to the one given by the commercial power supply, we induce larger eddy currents as it can be seen from the absolute maximum reached by the pick-up coil voltage. Nevertheless, the eddy-current-induced magnetic field transient is compensated by the reversal of the coils current.

In the next test, we try to reduce the settling time by reducing the Lenz effect decay. This compensation is achieved by removing the short across the Zener diodes. In this case, a current will flow through the protection diodes *only* when the voltage at the node OUT in Fig. 2 will be larger than the respective Zener voltage. Consequently, a larger amount of the compensating current from the power supply will flow through the quadrupole coil. This effect is shown in Fig. 7(b), where the time constants for the induced eddy current magnetic flux transients, solid and dashed

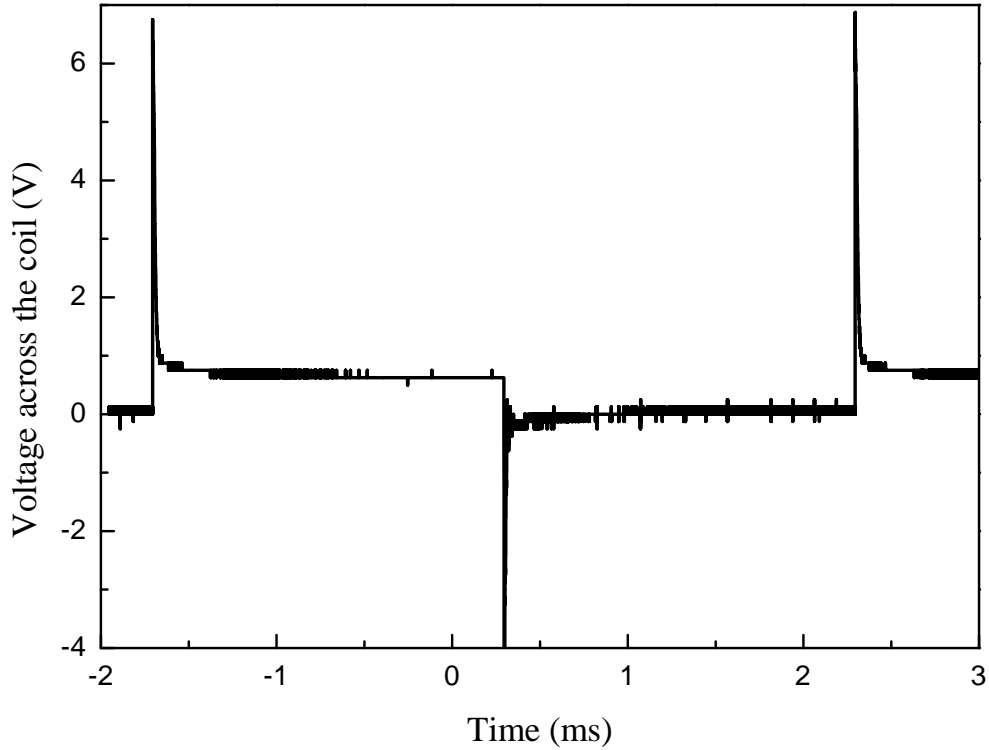


FIG. 6: Transient response of the voltage across the MOT coils.

lines, are $200 \mu\text{s}$ and $150 \mu\text{s}$, respectively. The settling time, or the overall transient duration, is now around $90 \mu\text{s}$.

As it was mentioned in the introduction, the magnetic field transients induced by eddy currents can wash out the samples of cold atoms prepared in the MOT. Therefore, we used this fact in order to perform our ultimate test of the driver. Using a sample of cold caesium atoms (at around $120 \mu\text{K}$), we realized an experiment similar to a previous one presented in [10]. In short, we built a Mach–Zehnder interferometer around the cell containing the cold atoms and we measured the phase shift that a probe laser pulse, with around 10^7 photons, experience after interaction with the atoms. The laser was red detuned by 25 MHz from the Cs cycling transition $6S_{1/2}(F=4) \rightarrow 6P_{3/2}(F'=5)$. The used protocol for this measurement was as follows:

- we trap the atoms during 3 seconds;
- the magnetic quadrupole field, the trapping and the repumper lights are turned off during 10 ms and, we fire a pulse train with 100 probe pulses (pulse duration $2 \mu\text{s}$, repetition period $6 \mu\text{s}$) that interact with the atoms;
- during 8 ms we turn on the trapping light only to remove the atoms from the probing region;

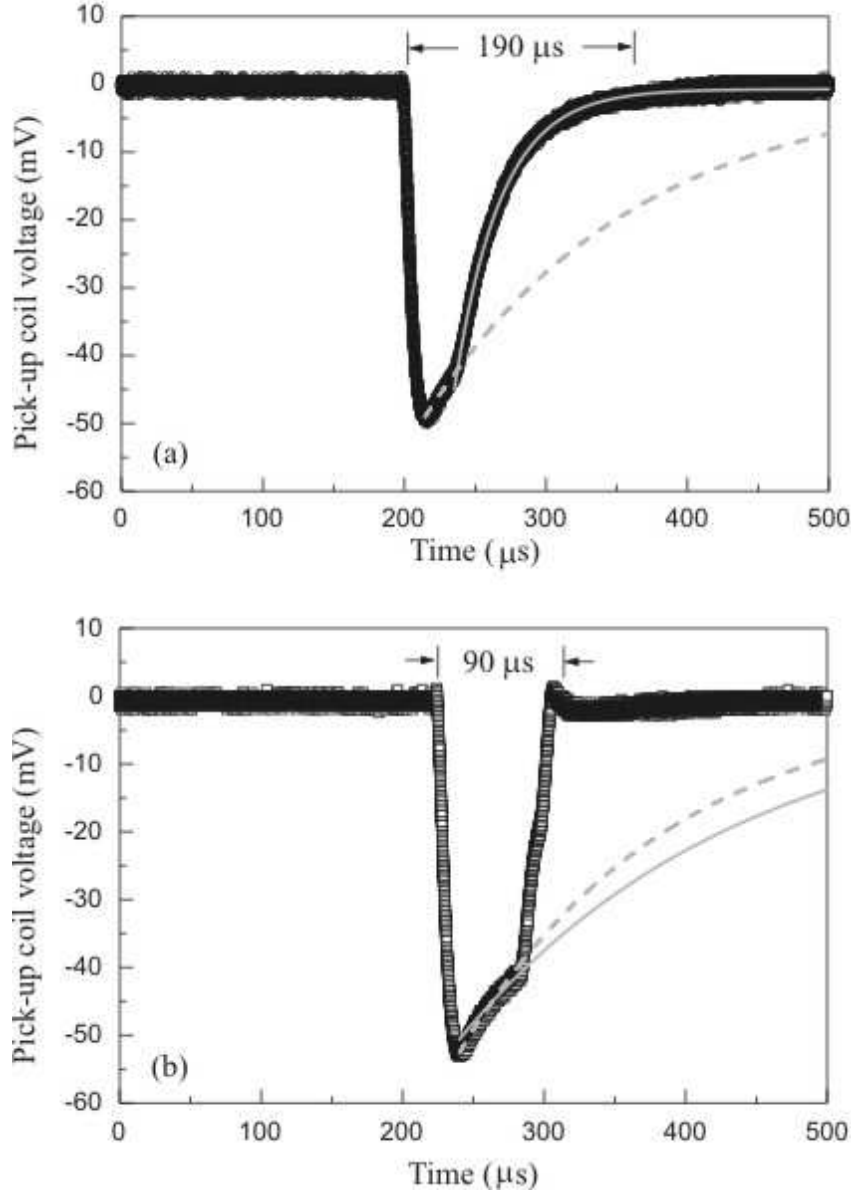


FIG. 7: (a) Compensation of the magnetic field transient induced by eddy currents (dashed line). The decay constant, obtained from the single exponential fit (solid line) to the Lenz effect transient, was $32.57(2) \mu\text{s}$. (b) Transient speed-up by compensation of the Lenz effect.

- we take a reference measurement with another sequence of 100 pulses.

The above steps are repeated 50 times in order to obtain a reliable data and the results are presented in Fig. 8. In one case the experiment is done switching the quadrupole magnetic field with the commercial unit and in the other with the driver.

The traces covering the first 600 μs represent the probe phase shift after the interaction with the atoms. The results of the reference measurement, probe phase shift in the absence of atoms,

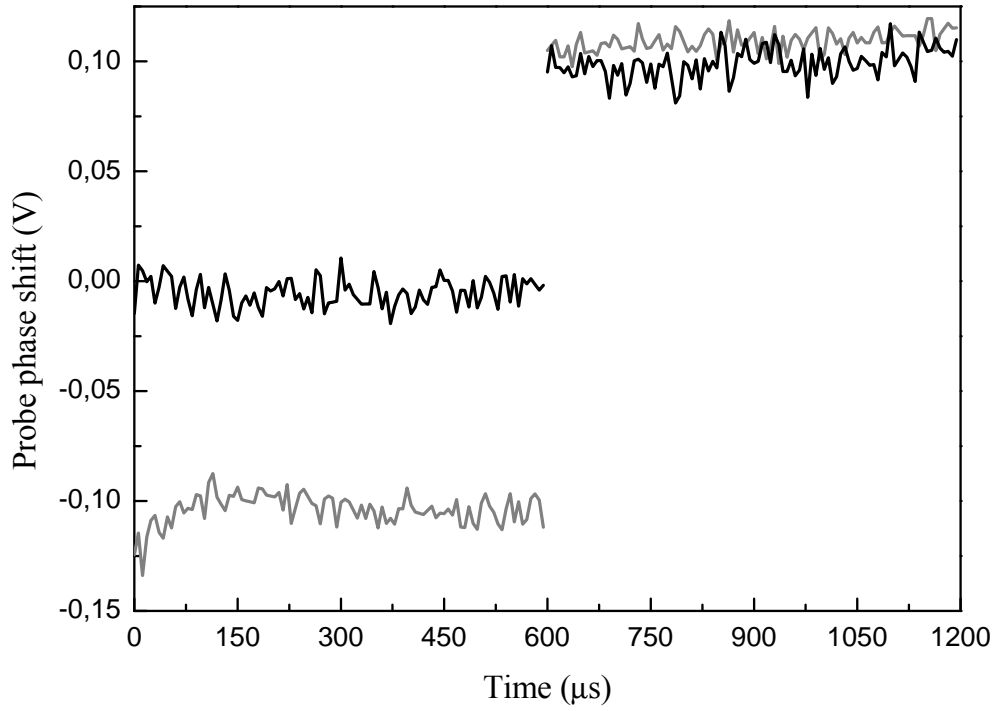


FIG. 8: Phase shift experienced by laser pulses after the interaction with a sample of cold atoms. The gray (black) traces correspond to the situation in which the current in the MOT coils is switched using the driver (commercial unit).

cover the interval starting from $600 \mu\text{s}$ up to $1200 \mu\text{s}$. As it can be seen from the Fig. 8, the measured atomic contribution when the quadrupole magnetic field of the MOT is controlled by the driver (gray traces) is larger than the atomic contribution measured when the control is done by the commercial unit (black traces) and without the possibility of compensation of magnetic field transients due to eddy currents. Since the reference measurement results are at the same level in both cases, we can without ambiguity attribute the reduction in the signal to the fact that less atoms are probed by the laser pulses.

Finally, from Fig. 7 it is clear that the magnetic field can be switched off about 100 times faster than in the case without polarity change of the coils' current. This dramatic reduction of the transition time from the millisecond down to the microsecond time scale, demonstrate once again that one of the key factors in the compensation of the undesirable eddy-current-induced magnetic field transients is the possibility of changing very fast the polarity of the current in the MOT quadrupole coils. In that way, we can overshoot or undershoot the current during the transitions, providing the necessary magnetic flux for the compensation of stray magnetic fields.

Acknowledgments

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- [1] See, for example, P. Horowitz and W. Hill, *The Art of the Electronics* (Cambridge University Press, 2001), 2nd ed.
 - [2] V. Kuperman, *Magnetic Resonance Imaging: Physical Principles and Applications* (Academic Press, 2000).
 - [3] D. J. Jensen, W. W. Brey, J. L. Delayre, and P. A. Narayana, *Med. Phys.*, **14**, 859 (1987).
 - [4] V. Senaj, G. Guillot, and L. Darrasse, *Rev. Sci. Instr.*, **69**, 2400 (1998).
 - [5] Y. Chung, Argonne National Laboratory LS note 148 (1990), www.aps.anl.gov/techpub/lnotes/l148/l148.html
 - [6] M. Alecci and P. Jezzard, *Magn. Reson. Med.*, **48**, 404 (2002).
 - [7] C. J. Dedman, K. G. H. Baldwin, and M. Colla, *Rev. Sci. Instr.*, **72**, 4055 (2001).
 - [8] A. Clairon, P. Laurent, G. Santarelli, S. Ghezali, S. N. Lea, M. Bouhara, *IEEE Trans. Instrum. Meas.*, **44**, 128 (1995).
 - [9] <http://www.penzar.com>
 - [10] D. Oblak, P. G. Petrov, C. L. Garrido Alzar, W. Tittel, A. K. Vershovski, J. K. Mikkelsen, J. L. Sorensen, and E. S. Polzik, quant-ph/0312165 (submitted to *Phys. Rev. A*).
 - [11] For ultimate protection an optocoupler can be properly added